logistics

MDPI

Article

Empirical Performance Measurement of Cargo Handling Equipment in Vietnam Container Terminals

Huy Tung Pham [1] and Luong Hai Nguyen [2,*]

[1] Department of Personnel & Administration, Vietnam Maritime University, Haiphong 180000, Vietnam; phtung@vimaru.edu.vn
[2] Department of Construction Economics, University of Transport and Communications, Hanoi 100000, Vietnam
* Correspondence: hainl@utc.edu.vn

Abstract: *Background*: Cargo-handling equipment (CHE) plays a vital role in maintaining the efficiency of a highly-worked container terminal. *Methods*: This study is aimed to analyze the CHEs' performance, which is conducted based on a contextual application of the overall equipment-effectiveness (OEE) technique and data collected from a field survey in 14 container terminals in Vietnam. *Results*: The findings reveal that the CHEs are operated incompatibly with their actual capacity due to low performance. Also, the findings clarified the unproductive exploitation of container terminals and low actual terminal throughput since the capacity-designed terminals are currently operating above their actual capacity. *Conclusions*: The application of the OEE index for groups of CHE equipment is an origin for the impact assessment of the overall performance between the groups of CHEs' equipment, thereby proposing management tools for supporting the improvement of the CHEs and container terminals' performance in Vietnam.

Keywords: cargo-handling equipment; container terminal; exploitation; overall equipment effectiveness; handling cycle time

check for updates

Citation: Pham, H.T.; Nguyen, L.H. Empirical Performance Measurement of Cargo Handling Equipment in Vietnam Container Terminals. *Logistics* **2022**, *6*, 44. https://doi.org/10.3390/logistics6030044

Academic Editors: Mladen Jardas, Robert Handfield, Pietro Evangelista, Predrag Brlek, David Brčić, Zlatko Sovreski and Ljudevit Krpan

Received: 3 May 2022
Accepted: 27 June 2022
Published: 4 July 2022

1. Introduction

Recently, shipping containerization has become a megatrend in the world [1]. The development of large-tonnage container ships in the world, the growth of container throughput in Vietnam, and the increasingly fierce competition in the international shipping market have put increasing pressure on Vietnam's seaport system [2–4]. Specifically, with the strong growth rate of the shipping industry, Vietnam has the third-largest container throughput in the ASEAN region, coming after Singapore and Malaysia, the countries with the most impressive growth in container throughput in the world. According to the World Bank, container throughput through Vietnam's seaports had a compound growth rate of 10.9% in the period 2010–2017, compared with the world average of 4.3%, East Asia of 4.5%, and South Asia of 6.0% [5]. Despite many competitive advantages in the container-shipping market, Vietnam's container terminals are still facing major challenges due to several shortcomings related to terminal location [6], transshipment and handling equipment [7], and operation management.

In the Southern part of Vietnam, in the Cai Mep-Thi Vai port cluster area, the favorable geographical location and modern CHE have facilitated Tan Cang—Cai Mep International Terminal (TCIT), Tan Cang—Cai Mep Container Terminal (TCCT), Cai Mep International Terminal (CMIT), and Tan Cang—Cai Mep Thi Vai Terminal (TCTT) ports to receive large-tonnage ships, and, therefore, they have undertaken an overwhelming majority of the container throughput of ports in the South of Vietnam. Conversely, Saigon International Terminal Vietnam (SITV), SP-PSA International Terminal (SP-PSA), and SP-SSA International Terminal (SSIT) mainly handle bulk cargo due to unfavorable location or old CHE (invested since 2010), and they are currently not suitable for modern ships [5].

In the Northern part of Vietnam, many container terminals in Hai Phong have paid attention to vertical investment, mainly upgrading CHE in terminals. Specifically, by 2018, the container terminals in the Hai Phong seaport area had invested in the most modern handling system and warehouse system to receive container ships. Chua Ve, Dinh Vu, and Tan Vu container terminals, and many newly-built container terminals (e.g., Nam Hai Dinh Vu Port, Vip Green Port, Nam Dinh Vu Port, and Lach Huyen Port) are equipped with modern handling equipment, which meets the needs of current port operations. The remaining ports use out-of-date handling-equipment systems, some of which do not even buy CHE but hire them for seasonal exploitation instead. The actual capacity of terminals in the Hai Phong area from 2020 to 2030 is expected to increase by 10–20% compared to the current design capacity after handling technology and exploitation management technology are innovated [8].

Numerous studies of factors affecting productivity and efficiency in container terminals have been conducted [9–11], but the results have rarely emphasized analyzing the CHEs' operations and performance that inherently influence the container terminals' performance. These scare analyses are attributed to a matter of data availability [12]. This practice is in line with the field survey of this study, in which very few data have been recorded and/or reservedly made public due to the terminals' privacy policies. The recent related work of Jorge H. Luna et al. [12] used the data-envelopment analysis (DEA) technique to assess the efficiency of CHEs' operations, thereby the findings indicated that spending more on hours in CHE operations of a containership could decrease the probability of providing an efficient terminal service. However, the DEA technique is criticized due to its measurement based on benchmarking [13], which does not take into account specific aspects, such as the maximum production capacity of the equipment of the CHE system [14]. There remain some old government-owned terminals in Vietnam with limited funds, in which many pieces of old CHE are still used for cargo handling and the management of CHE exploitation is still not productive [15]. As a result, the frequency of abnormal damage to CHE is increasing; that is, the time to stop the machine for urgent maintenance and repair is longer, which has significantly affected the productivity and exploitation performance of the CHE and has caused the waste of port resources. Thus, this study employs the overall equipment-effectiveness (OEE) technique that could compare the CHE operation levels with the ideal and expected performance of a piece of CHE [16,17] and consider the specific performance of the CHE in use, the quality and the performance level [18,19].

This study aims to clarify the empirical performance of the CHE and container terminals based upon an application of OEE approach using collected data of CHE activity in a period with normal production conditions. The application was to calculate indicators in terms of availability, performance, quality, and OEE of each CHE as well as of the whole group of CHE, thereby comparing and clarifying the cause of performance decrease and proposing strategies to improve the performance of the CHE and container terminals in Vietnam. The study design is structured in three sections. First, the methods are justified in terms of OEE technique for CHE and container terminal's performance measurement. Second, the empirical analyses results are presented with integrated discussions. In the final section, conclusions are drawn.

2. Literature Review

In the work of Jo and Kim [20], key performance indicators were used to assess the ship-to-shore cranes, which are based on the hourly metrics for each movement in terms of the hoist, trolley, gantry, and boom. The study applied the mean movements between failure (MMBF) and the mean time to repair (MTTR) indicators to assess performance for one type of equipment, the STS shore cranes. This application failed to evaluate the overall efficiency of each piece of CHE equipment and the influence of each group CHE. Mouafo Nebot and Wang [21] used the ECOGRAISIM approach to measure single-rate performance, including valid resource utilization rates, quality of service ratios, and the number of transferred containers. Accordingly, the non-optimized resource usage in the mode setting also grants those with a significant negative impact on the CHE's performance. However, these indicators were evaluated sporadically, without clarifying specific influencing factors, thereby proposing strategies to control and improve them. The OEE has been applied to the frontline operation of the terminals [22], with an examination of some of the critical equipment influences on frontline operations, such as shoreline cranes and supported equipment. However, the study did not measure each piece of equipment as well as group equipment in the frontline. Likewise, Mazloumi and van Hassel [23] calculated OEE for the general operation of the port, which mentioned the influence of groups of loading and unloading equipment, such as shore cranes, yard cranes, trucks, and so on. However, the OEE for each equipment and group of equipment of CHE was not taken into account. Although previous works have applied the OEE to the general terminal operation and suggested the influence of the equipment and the group of loading and unloading equipment, there is no focus on the analyses of the OEE for each piece of equipment and group of CHEs of the container terminal.

The application of OEE helps dissect and simplify a complex relationship between the factors affecting the productivity of each CHE as well as the group of CHEs. To improve the OEE and the efficiency of the CHE, it is necessary to have the direction management from the relevant departments, divisions, departments, and individuals promptly proposing solutions to overcome the problem caused by each party in the production process. Thus, the assessment of OEE for CHE shows the relationship between relevant departments and individuals, thereby performing the management functions of the CHEs well.

The OEE technique is built on three indicators, including the availability, performance, and quality of equipment [16], which are used to measure the performances of individual pieces of equipment in processes disregarding their relations with the other pieces of equipment, or even with the people involved in their operations. Thus, the results of OEE determine decisions involving the operation of equipment [24,25]. According to the concept of total productive maintenance (TPM), one of the major culprits of waste and loss in production is the availability losses that reduce efficiency in CHE use, productivity, and product quality [26]. Also, the overall equipment effectiveness (OEE) in TPM is the most widely-used standard in the world to measure the productivity and operating efficiency of a machine and equipment percentage-wise (%) [27–29].

3. Materials and Methods

3.1. Methods for Measuring the CHE Performance in a Container Terminal

The CHE includes many specialized vehicles and equipment which determine the exploitation capacity of container terminals. CHE is, mainly, arranged at the front line and rear line of container terminals. Generally, CHE is classified by technical characteristics and working conditions, including: (1) the group of quay cranes (QC/Liebherr); (2) the group of yard cranes (RTG/RMG); (3) the group of lift-on/-off vehicles (reach-stackers, straddle-carriers, and top-loaders/-lifters); and (4) the group of yard tractors.

OEE can be used to monitor the performance of a production process, help businesses identify problems in equipment use and maintenance, determine the percentage (%) of efficient production time, and is the standard to track progress in fixing these problems. Particularly, an OEE score of 100% represents perfect performance, which means no downtime, smooth and fast production, and good-quality products. The comparison of the performance of CHE at different times can show the effectiveness of the management and exploitation of the CHE, thereby closely monitoring the CHE operation process.

The OEE index includes factors of availability, performance, and quality [16]:

a. The availability level of a group of CHE (A):

Availability-A: Comparison of the time it takes for the machine to actually produce the product with the potential operating time.

Availability is concerned with machine downtime and is calculated as [27–29]:

$$A \frac{\text{Operating Time}}{\text{Planned Production Time}} \times 100\% \tag{1}$$

This study applied for calculating availability to a CHE (Ai): ratio of equipment operating time and equipment planned production time (in month or quarter or year).

$$A_i = \frac{T_{OTi}}{T_{PPTi}} \times 100\% = \frac{T_{PPTi} - T_{PDi} - T_{UDi}}{T_{PPTi}} \times 100\% \tag{2}$$

The availability of a CHE group (A) is determined by the average value of the availability of pieces of equipment in the same group.

$$A_G = \frac{\sum_1^n A_i}{n} \tag{3}$$

Detail:

- n: number of pieces of equipment in a CHE group;
- Ai: availability of the i-th equipment in the CHE group;
- A_G: availability of the CHE group;
- T_{OTi}: operating time of the i-th equipment;
- T_{PPTi}: planned production time of the i-th equipment;
- T_{UDi}: unplanned downtime of the i-th equipment;
- T_{PDi}: planned downtime of the i-th equipment;
- The planned downtime of equipment includes shift-break time, meal breaks, scheduled preventive maintenance time (inspection, inspection, maintenance, and repair, according to the regulations of each terminal), and downtime is not according to the terminal's regulations due to other objective reasons (e.g., no production plan, wind, and storm); and
- The unplanned downtime of equipment includes downtime for emergency maintenance, abnormal damage repair, and downtime due to other subjective reasons that could be estimated.

b. Performance of CHE group (P):

Performance-P: comparison of actual output with what the machine can produce in the same time.

Performance is concerned with machine speed loss and is calculated as [27–29]:

$$P = \frac{\text{Total pieces / Operating time}}{\text{Ideal run rate}} \times 100\% \tag{4}$$

$$P = \frac{\text{Total pieces} \times \text{Ideal cycle time}}{\text{Planned production time} - \text{Downtime}} \times 100\% \tag{5}$$

Ideal cycle time is the theoretical fastest time to produce a product in minutes. This parameter is usually measured and calculated by different complicated methods, depending on the type of equipment. Ideal cycle time when multiplied by theoretically produced totals gives the ideal total production time, which is the theoretical fastest time to produce the intended total number of products.

Container-handling activities at seaports include many handling options, corresponding to different numbers and types of vehicles, and the execution time of container-handling activities is random. The working cycle of each vehicle depends not only on the handling operation time of this vehicle, but, also, on the waiting time for coordination among vehicles and equipment in a handling option. For example, the tractor trailer may have arrived to receive the container, but the quay crane has not finished loading the container onto the ship to bring it to the tractor trailer, so the tractor trailer has to wait. The crane has already brought the container to the parking spot but the tractor trailer has not turned up yet, so the quay crane must continue to hold the container and wait for the arrival of the tractor trailer to place the container onto it. For each vehicle type, the cycle for each operation depends on the vehicle's mechanical cycle, on design, and on the container position. For example, for the same operation of unloading the container from the ship to the tractor trailer, the quay crane will spend more time to take the container below the deck (cargo hold) compared with the container above the deck. Or when the tractor trailer puts the container into the yard, the position of the container (at the beginning or the end of the yard) will affect the travel time of the tractor trailer in the container yard [30].

For maximizing container-terminal operation, it must be understood that terminal throughput is different to the actual throughput during operations and the actual throughput by job step (in TEU or Ton). In fact, the planning and arrangement of containers on the ship and in the container yard, and the situation of storing containers in the yard of the port, and other needs of customers will affect the situation of stacking containers into many layers and increasing the amount of shifting when handling containers, thereby affecting the cycle time of the steps in the operation. Therefore, despite the terminal throughput, the actual throughput by job for CHEs can be higher than the terminal throughput as the container has to be shifted many times. In addition, each type of CHE has a different maximum container-handling capacity, depending on the type of vehicle, the loading and unloading plan (vessel–tractor trailer, tractor trailer–yardT, and so on), coordination in operations, continuity in the process, and so on.

Therefore, in order to evaluate the working intensity of the equipment, the performance of each group of CHEs cannot be evaluated according to the terminal throughput, but the actual throughput by job step.

This study applied for calculating the performance of a piece of equipment (Pi) as follows (month or quarter or year):

$$P_i = \frac{(M_{RATi} \times K_C) \times \text{Ideal cycle time}}{T_{PPTi} - T_{PDi} - T_{UDi}} \times 100\% \quad (6)$$

The performance of a CHE group (P_G) is determined by the average value of the performance of pieces of equipment in the same group.

$$P_G = \frac{\sum_1^n P_i}{n} \quad (7)$$

Detail:

- n: number of equipment in a CHE group;
- Pi: performance of the i-th equipment in the CHE group;
- P_G: performance of the CHE group;
- M_{RATi}: real actual throughput by job step (including the real actual throughput by job step of delivery containers, the throughput of shifting containers, the throughput of inspection containers, the throughput of unloading containers, the throughput of empty containers, etc.) of the *i*-th equipment. The unit of measure is TEU; and
- K_C: conversion coefficient for the number of TEUs transported in containers 1 MOVE of a group of equipment of the same type (in fact, each time the spreader is lifted, the quay crane QC can lift one 20′, 40′, or 45′ container or two 20′, 40′, or 45′ containers or four 20′ containers and each time the spreader is lifted, an RTG crane and reach-stacker can lift one 20′, 40′, or 45′ container or two 20′ containers. Therefore, each time the spreader is lifted and lowered (1 MOVE), the equipment can lift more than 1 TEU, so each terminal needs to set up a conversion factor Kc for each type of port equipment). (TEU/MOVE).

c. Quality of the CHE group (Q):

Quality-Q: the comparison between the quantity of products that meet the requirements and specifications of the customer with the quantity of products produced.

Quality is concerned with the loss of quality, which is calculated as [27–29]:

$$Q = \frac{\text{Good pieces}}{\text{Total pieces}} \times 100\% \tag{8}$$

This study was applied to calculating the quality of a single piece of equipment (Q_i): ratio of the total real actual throughput by job step of the required quality to the total real actual throughput by job step of the equipment (monthly, quarterly, or yearly).

$$Q_i = \frac{M_{RATQi}}{M_{RATi}} \times 100\% \tag{9}$$

The quality of a CHE group (Q_G) is determined by the average value of the quality of the pieces of equipment in the same group.

$$Q_G = \frac{\sum_1^n Q_i}{n} \tag{10}$$

Detail:

- n: number of pieces of equipment in a CHE group;
- Qi: quality of the *i*-th equipment in the CHE group;
- Q_G: quality of the CHE group; and
- M_{RATQi}: Real actual throughput by job step to ensure required quality (container handling on schedule, not damaged during transportation) of the *i*-th equipment. The unit of measure is TEU.

d. Overall equipment efficiency (OEE) formula for a CHE group:

Formula for calculating OEE: OEE is concerned with all three factors above, and is calculated as [27–29]:

$$OEE = A \times P \times Q/10^4 \tag{11}$$

This study was applied to calculating the OEE of a single piece of equipment (OEEi) and for the CHE group (OEE_G) in month, quarter, or year.

$$OEEi = A_i \times P_i \times Q_i/10^4 \tag{12}$$

$$OEE_G = A_G \times P_G \times Q_G/10^4 \tag{13}$$

3.2. Methods for Measuring the Performance of Container Terminals

Terminal performance is evaluated through the development of criteria to assess the level of completion in internal operations and customer satisfaction with services. The coordination and uniform operation within the terminal will improve service quality and customer satisfaction, thereby creating efficient terminal exploitation. The task of developing criteria to help evaluate the efficiency of container-terminal exploitation, both internally and with customers, is always an important task. Container-terminal managers, whether port authorities or terminal operators, need to organize complex processes efficiently to find the best ways to bring value for customers and solve problems for the stakeholders.

Figure 1 show that, the efficiency of a port is affected by some operations of continuum, including maritime, terminal, and hinterland operations [31]. The links in this chain are interrelated, since inefficiencies in one link are likely to have an impact on the others. For instance, issues in terminal operations are most likely to cause delays in maritime and hinterland operations.

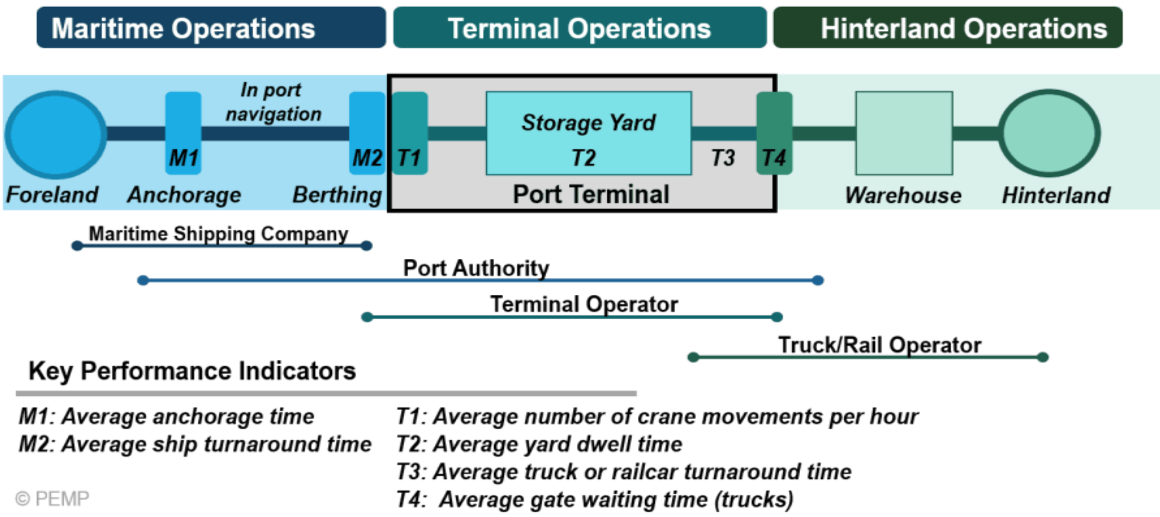

Figure 1. Continuity of container terminal operations.

Maritime operations: The efficiency of the maritime access is a component of port performance, which includes average anchorage time (M1) at an available berthing slot. What happens at the port foreland, mainly because a ship could be delayed, can have an impact on its performance. Long average anchorage time at anchorage can be the outcome of a lack of berthing slots able to accommodate specific ship classes (e.g., draft and cargo types), as well as terminal productivity issues. It depends on their sites and configurations, and navigation in terminals may require pilotage and tugs through access channels and turn basins. The average ship turnaround time (or ship dwell time; M2) represents the amount of time needed to work on a ship once it has docked. Therefore, container terminals need to strengthen the system to serve maritime operations at the port foreland to ensure the interests of shipping companies are catered to.

Terminal operations: Performance of container-terminal operation commonly involves several key operations. Crane performance (T1) is a common bottleneck, depending on the average number of crane movements per hour. For maritime shipping companies, this is a crucial factor in port service activities, since it is related to their ships' time in port. How the cargo (that is, containers) is brought back and forth to the storage yard is also a component of port performance and is often related to the number of movements per crane hour. Many container terminals use trailer tractors or straddle-carriers for such operations. The stacking activity and stacking density of containers at the storage yards are important variables that determine the capacity of the container terminal. The average yard dwell time (T2) for inbound, outbound, and transshipment cargo is a common indicator of terminal performance. When trucks enter the terminal to pick up or drop off cargo, space and equipment are required. This is often a critical bottleneck for trucking companies since it dictates the amount of time they will spend at the terminal, which is reflected in the average truck turnaround time (T3). Gate performance depends on the efficiency of tasks related to document processing and security inspections for a truck to be admitted and cleared to pick up or drop off cargo at the facility. Gates which are used above their capacity often feature long truck lines waiting to be processed and enter the terminal for cargo they are already chartered to handle. Therefore, the average gate waiting time (T4) can be used as a performance indicator. For terminals having on-dock rail facilities, the performance of the rail loading/unloading of equipment can also be an important component of the terminal's performance.

Hinterland operations: The efficiency of transport operations beyond the terminal is usually not considered as a port performance indicator. This involves all the transport and distribution activities servicing the port's customers, such as an inland port. However, for practical purposes, it generally focuses on inland operations adjacent to the port area (often labeled as the back of port). The key factor in hinterland operations is the capacity of the local road network in areas adjacent to the port. Congestion and bottlenecks at street intersections impair the port's performance in many of the supply-chain management strategies of the port's customers. Some ports have near-dock rail yards that must be serviced through the terminals' gates. In many gateway ports, transloading activities that transfer the contents of maritime containers into domestic truckloads (or domestic containers), or vice versa, are an element of the performance of hinterland operations. Port authorities have an oversight, either directly or indirectly, of the port efficiency.

The aforementioned performance-evaluation criteria of container terminals are all commonly used international criteria to evaluate the performance of seaports. Especially for the operation of the container terminal, these criteria are closely related to the main operation. The performance of quay cranes, which is determined by the average number of crane movements per hour (T1), is a common bottleneck. This can affect the ship's clearance capacity of the front line, help measure equipment-handling capacity during working hours/shifts/working days, and is an important factor as it relates to the time the customer's vessel is in port and to the customer's interests [31].

Operational efficiency of a container terminal is an important measure of competitiveness among container terminals, which is measured by customer satisfaction, productivity, and performance indicators of seaports [32,33]. The most sensitive factors affecting container-terminal performance are terminal capacity and crane productivity [34].

The performance of a terminal depends on many factors, including throughput capacity on loading and unloading lines (especially the front line), performance of terminal yard operations, the readiness level of CHEs, performance of CHEs, operational quality of CHEs, and so on. The performance of a terminal is assessed through the ratio between a terminal's implemented capacity and designed capacity [5,35].

$$\text{Performance of terminal} = \frac{\text{Terminal's implemented capacity}}{\text{Terminal's designed capacity}} = \frac{\text{Terminal throughput}}{\text{Design throughput of terminal}} \tag{14}$$

Terminal operators always want to optimize a terminal's capacity, which means that a terminal can operate at 100% capacity while minimizing unloading time. However, this is very difficult to achieve in reality. It is commonly admitted that dock utilization performance at 65% will give the highest efficiency. If it is higher, the situation of waiting ships will occur, resulting in congestion, reducing service quality at the terminal, and then delaying the ship's schedule [36].

3.3. Data Collection

This study conducted a field survey of 14 container terminals in the North of Vietnam (Table 1), which features a large sea, an island, and a long coastline, located in the sea region of Vietnam. This area has 126 km of coastline and more than 4000 km^2 of sea surface, operating with multiple functions, holding strengths, and strategic positions in the socio-economic development of the North of Vietnam and international trade. This area is an import hub due to its position as a trade gateway to the North, due to its being a gateway to the sea connecting with the rest of the world, and due to its being a place located in the industrial economic zone of the North Coast (i.e., Hai Phong, Quang Ninh, Thai Binh, and Nam Dinh). The volume of goods passing through has continuously increased, and, accordingly, the port systems have also been expanding for years. According to the master plan for the development of Vietnam's seaport system up to 2020, with a vision for 2030 approved by the Prime Minister in Decision No. 1037/QD-TTg dated 24 June 2014, these seaport systems are being developed as the main gateway port (class IA) for import and export of goods from Vietnam in the Northern region. The goal of the master plan has been to focus on building international gateway ports to receive container ships of up to 8000 TEU or larger, capable of combining the roles involved in international container transshipment.

Table 1. Descriptions of container terminals in the North of Vietnam.

TT	Terminals	Wharves			Yard		Warehouse		Design Capacity (TEU)	Construction Year
		Quantity	Lengths (m)	Dead Weight Tonnage (DWT)	Type	Area (m^2)	Area (m^2)	Type		
1	NAM HAI	1	145	10,000	Container	66,540			200,000	2008
2	GREEN PORT	2	350	20,000	Container	75,000	6000	CFS	300,000	2004
3	CHUA VE	5	848	40,000	Container	230,000	3400	CFS	600,000	2002
4	TAN CANG 128	1	295	15,000	Container	165,000	2500	CFS	350,000	2014
							2500	Bonded Warehouse		
5	HAI AN	1	150	20,000	Container	150,000	4000	CFS	350,000	2009
6	TAN CANG 189	1	160	10,000	Container	85,142			150,000	2011
7	PTSC DINH VU	1	250	20,000	Mix	2500			350,000	2007
					Container	81,500	3240	CFS		
8	DINH VU	2	425	20,000	Mix	200,000			650,000	2002
9	TAN VU	5	980	40,000	Container, mix	600,000	4000	CFS	1,000,000	2017
10	NAM HAI DINH VU	1	450	40,000	Container	200,000			550,000	2013
11	VIP GREEN PORT	2	378	40,000	Container	200,000			500,000	2014
12	NAM DINH VU	2	440	40,000	Container	250,000			500,000	2017
13	HICT (LACH HUYEN)	2	750	100,000	Container	400,000			1,000,000	2017
14	MIPEC	2	380	40,000	Container	130,000	10,000	CFS	250,000	2020

4. Results and Discussion

4.1. Performance of CHEs in Container Terminals

According to the actual statistics of surveyed container terminals in Vietnam, conductied in stable and continuous working conditions, the average productivity of CHEs and their average handling-cycle times are shown in Table 2. This indicates that the productivity of CHEs depends on the type of CHE, the vessel size, the terminal size, and the qualifications of the CHE operator. The CHEs of the same type and quality in container terminals have the same average productivity.

Table 2. Average productivity and average handling-cycle times of some common types of CHEs observed and statistics in surveyed container terminals in Vietnam.

No.	Type of CHE	Average Productivity of CHE (Move/Hour/CHE)	Average Handling-Cycle Time of CHE (Minute)
1	Quay crane (QC)	25	2.4
2	Quay crane (Tukal)	20	3
3	Yard crane (RTG—rubber-tire gantry crane)	25	2.4
4	Lift-on/lift-off vehicle (reach-stacker)	25	2.4
5	Lift-on/lift-off vehicle (top-loader/-lifter)	30	2
6	Yard tractor	8	7.5

Table 3 shows that the average working hours of CHE groups are less than 12 h/day. For The rubber-tired gantry (RTG), the code RTG 05 has the lowest average operating hours of 1.57 h/day, compared to the code RTG 12 with the highest average operating hours of 7.83 h/day. As for the group of quay cranes, the average operating hours of the two quay cranes located between the piers with code QC 02 is 11.13 h/day and QC 03 is 11.12 h/day, while the average operating hours of two shore cranes located at the beginning and the end of the piers with code QC 01 is 7.56 h/day and QC 04 is 9.31 h/day. Therefore, even though the operating capacity of the CHE groups is quite large, the average number of working hours of the CHE group in a month is relatively low, and the number of operating hours of CHE in the same group is not equal, due to: the number of ships docked and container cargo through the port; containers stored in yards and waiting for delivery; and the number of vehicle operators is less than the port's number of vehicles. These findings indicate that the management of CHEs is not effective. That is, the CHEs' capacity has not been fully utilized and there is an imbalance in the number of operating hours among CHEs in the same group. The operating hours of the quay crane located in the middle of the piers are higher than that of the quay crane located at the beginning and the end of the piers.

Table 3. Hours of operation/month of vehicle/equipment in Nam Dinh Vu terminal.

No.	Type of Vehicle	Code of Vehicle	Operating Hours Indicator on the First Day of the Month	Operating Hours Indicator on the Last Day of the Month	Hours of Operation/ Month	Average Operating Hours/Day
1	Ship-to-shore crane	QC 01	6388.74	6615.59	226.85	7.56
2	Ship-to-shore crane	QC 02	11,283.87	11,617.69	333.82	11.13
3	Ship-to-shore crane	QC 03	11,569.43	11,902.89	333.46	11.12
4	Ship-to-shore crane	QC 04	8870.55	9149.76	279.21	9.31
5	Rubber-tired gantry	RTG 01	6169	6376	207	6.9
6	Rubber-tired gantry	RTG 02	6961	7191	230	7.67
7	Rubber-tired gantry	RTG 03	6577	6799	222	7.4
8	Rubber-tired gantry	RTG 04	5799	6017	218	7.27
9	Rubber-tired gantry	RTG 05	5621	5668	47	1.57
10	Rubber-tired gantry	RTG 06	5756	5950	194	6.47
11	Rubber-tired gantry	RTG 07	808	884	76	2.53
12	Rubber-tired gantry	RTG 08	401	626	225	7.5
13	Rubber-tired gantry	RTG 09	968	1070	102	3.4
14	Rubber-tired gantry	RTG 10	1016	1132	116	3.87
15	Rubber-tired gantry	RTG 11	901	1010	109	3.63
16	Rubber-tired gantry	RTG12	1511	1746	235	7.83
17	Forklift	NDV 01	9824	10,156	332	11.07
18	Forklift	NDV 02	9268	9617	349	11.63

Table 4 provides statistics on the throughput of each vehicle/piece of equipment and the average throughput of the CHE group at a container terminal in one year (12 months). As for the quay crane group (QC), the monthly throughput as well as the average annual throughput of the quay crane code QC 02 and QC 03, are always much higher than that of the quay crane code QC 01 and QC 04. As for the RTG group, the largest average throughput is 4200 TEU/month (RTG 02), the smallest average throughput is 1308 TEU/month (RTG 08) and there is a case where the monthly throughput of the crane is 0. Due to the low container throughput of QC quay cranes in January and February, the demand for yard crane RTG decreases, and, in order to save labor, the port does not allocate yard cranes code RTG 07-12 for exploitation, so there is no throughput for these means. In June, July, and August, although the container throughput of QC quay cranes is low, other RTG yard cranes still perform the job in terms of unloading containers on the yard for customers, and shifting and arranging containers on the yard; only yard crane code RTG 08 is not allocated for exploitation, so there is no throughput. It is obvious from Table 3 that the container throughput between the months for each vehicle is unstable and the average throughput of vehicles in the same CHE group is not equal; especially, the container throughput of quay cranes is frequently organized on 02 quay cranes with codes QC 02 and QC 03, located in the middle of the route, resulting in higher working intensity in a comparison with other 02 cranes.

Table 4. Container throughput of CHEs in Nam Dinh Vu terminal in one year (12 months).

No.	Code of Vehicle/ Equipment	Container Throughput of CHEs in 2021 (TEU)													
		January	February	March	April	May	June	July	August	September	October	November	December	Average Through-put of Vehicles /Month	Average Through-put of CHEs Group/Month
1	QC 01	4470	3733	5351	6617	6139	4361	5061	5895	5805	5911	5363	7083	5482	
2	QC 02	8702	6955	10,236	12,089	10,769	7178	6956	8502	9362	9430	8641	10,684	9125	
3	QC 03	8840	6788	10,773	9425	11,150	7846	6254	8191	9590	9074	8231	10,825	8916	7601
4	QC 04	6138	4565	8422	9053	9578	5257	4068	4763	7499	7223	7085	8917	6881	
5	RTG 01	2650	1900	2750	3600	4650	3500	3950	4550	3950	3900	3950	5350	3725	
6	RTG 02	3650	2850	4550	3950	5000	2850	4150	4650	4500	4050	4450	5750	4200	
7	RTG 03	6050	3250	3700	3450	2600	3200	4050	3900	3600	3550	3700	5500	3879	
8	RTG 04	4950	2750	4950	3800	4050	250	400	3400	4100	3800	3750	5550	3479	
9	RTG 05	5650	3100	4950	4150	4600	2850	2600	4050	3000	1600	1050	1150	3229	
10	RTG 06	5750	3200	1550	3200	4550	3550	3800	1900	2500	2100	2250	5200	3296	2915
11	RTG 07	0	0	2300	2250	3750	2050	1700	1950	2350	2100	1100	2000	1796	
12	RTG 08	0	0	400	500	50	0	0	0	1900	3150	4000	5700	1308	
13	RTG 09	0	0	3350	4150	2950	2300	1950	1800	2600	2250	1900	2450	2142	
14	RTG 10	0	0	3450	3600	3650	2450	2000	1850	2650	2600	2600	2900	2313	
15	RTG 11	0	0	2350	4250	2500	1600	1400	1750	2800	2800	2400	2650	2042	
16	RTG 12	0	0	4100	4400	4750	3450	4200	3950	4200	3750	4300	5800	3575	
17	NDV 01	2581	1982	3034	4441	2745	2859	2867	3066	4316	3339	2724	4134	3174	3105
18	NDV 02	2858	1419	2445	4189	3973	2923	2291	2926	3980	3114	2243	4081	3037	

Table 5 provides data on operation of a surveyed container lift-on/-off vehicle by month.

Table 5. Data on monthly operation of Nam Dinh Vu terminal's lift-on/-off vehicle during 12 months.

Month	Hours of Operation in a Month (h)	Times of Unlocking the Twistlock in a Month (Times)			Number of Kilometers in Operating 01 Month	Amount of Oil Supplied (Liter)	Remaining Amount of Oil in the Tank (Liter)
		Total	Container 20′	Container 40′			
January 2021	235	3405	1648	1757	535	2674	352
February 2021	190	2657	1350	1307	403	1957	159
March 2021	278	4073	2078	1995	635	3178	273
April 2021	337	5663	2444	3219	735	4049	305
May 2021	248	3638	1787	1851	571	2954	240
June 2021	266	3622	1526	2096	552	2845	353
July 2021	275	3733	1733	2000	586	2864	451
August 2021	300	4180	2229	1951	629	3135	416
September 2021	370	5482	2332	3150	701	3933	352
October 2021	304	4432	2186	2246	607	3197	368
November 2021	259	3693	1939	1754	460	2590	224
December 2021	332	5120	1972	3148	663	3544	368

Figures 2 and 3 show that the figures for the operation of a container lift-on/-off vehicle for 12 months fluctuate depending on the terminal container throughput and the real actual throughput by job step of the container lift-on/-off vehicle. Comparing the times of May and June in the two charts of Figures 2 and 3, the operating hours of the lift-on/-off vehicle increased, but the number of kilometers running of the lift-on/-off vehicle decreased, and the times of unlocking the twistlock were almost the same and the amount of oil supplied decreased. This shows that the time the lift-on/-off vehicle is operating but not moving and not unlocking the twistlock (or not handling) increases.

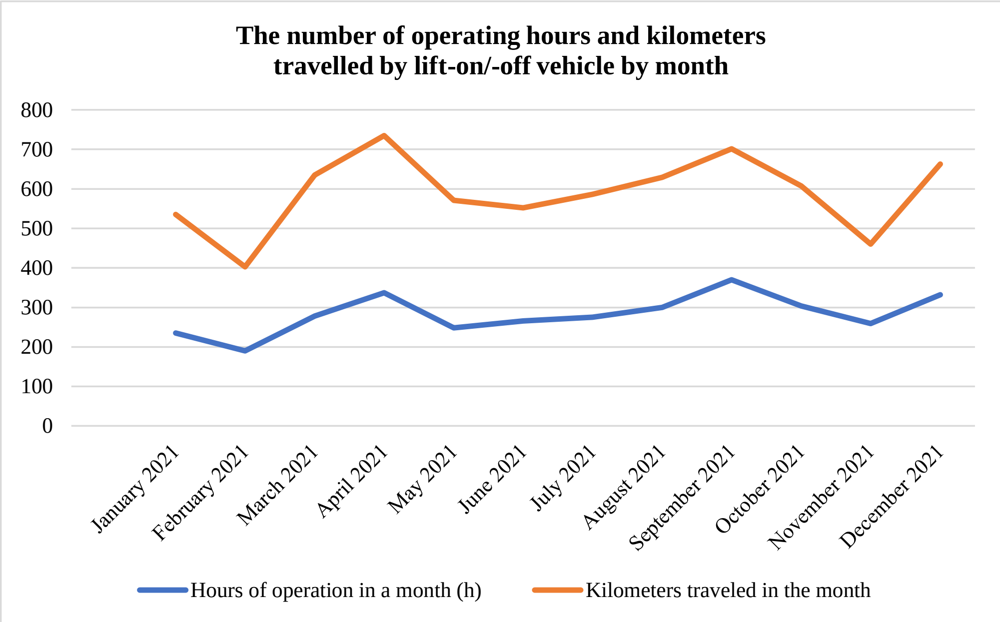

Figure 2. The number of operating hours and kilometers travelled of a container lift-on/-off vehicle by month.

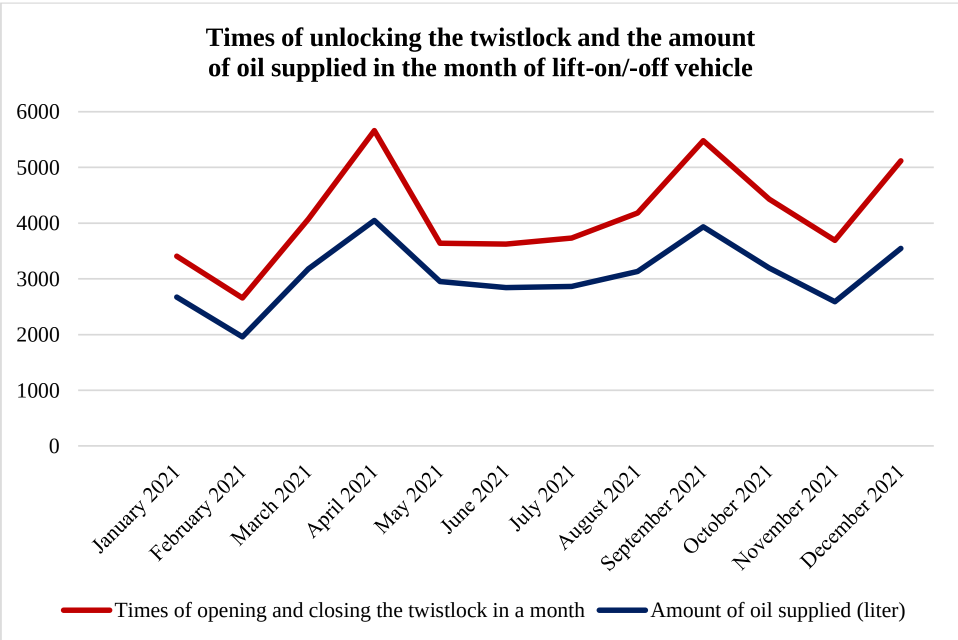

Figure 3. Times of unlocking the twistlock and the amount of oil supplied in the month of lift-on/-off vehicle.

During CHEs exploitation, the operating times and downtimes of each vehicle are monitored and aggregated weekly and monthly, as follows:

According to Table 6, the quay cranes (QC) and yard cranes (RTG) indicate the monthly downtimes due to maintenance, repair, and other reasons. The downtime data helps calculate the availability of the CHE group. For the quay crane group, the availability of the quay crane between the piers with code QC 02 is 46% and QC 03 is 47%, while the availability of the quay cranes at the beginning and the end of the route is 39%. For yard cranes, codes RTG 02 and RTG 12 have the same maximum availability of 31%, and for yard cranes code RTG 05 has the smallest availability at 6%. The analysis of data shows that: (1) the downtime has not yet been differentiated between scheduled/unscheduled maintenance and repair, and planned/unplanned downtime; (2) due to low throughput, some RTG yard cranes have low operating times; and (3) the availability of the quay crane located in the middle of the piers is higher than that of the quay crane located at the beginning and the end of the piers.

Table 6. The availability of quay cranes (QC) and yard cranes (RTG) in December 2021 at Nam Dinh Vu terminal.

Group of CHEs	Codes	Operating Time			Downtime			Total Exploitation Days in Month (Day)	Availability (Total Operating Time/Total Downtime)
		Total Operating Time (Day)	Normal Operating (Day)	Support Other Ports (Day)	Total Downtime (Days)	Time for Mainte-nance and Repair (Day)	Time for other Reasons (Day)		
Quay crane	QC 01	9.46	9.46	0	21.54	1	20.54	31	31%
	QC 02	14.25	14.25	0	16.76	0.67	16.09	31	46%
	QC 03	14.67	14.67	0	16.35	0.17	16.18	31	47%
	QC 04	12	12	0	19	0.25	18.75	31	39%
Yard crane	RTG 01	8.42	8.42	0	22.59	0	22.59	31	27%
	RTG 02	9.59	9.59	0	21.43	0.13	21.3	31	31%
	RTG 03	9.09	9.09	0	21.93	0	21.93	31	29%
	RTG 04	8.8	8.8	0	22.21	0	22.21	31	28%
	RTG 05	1.96	1.96	0	29.05	0	29.05	31	6%
	RTG 06	7.51	7.51	0	23.5	0	23.5	31	24%
	RTG 07	3.12	3.12	0	27.88	0	27.88	31	10%
	RTG 08	9.13	9.13	0	21.88	0	21.88	31	29%
	RTG 09	4.16	4.16	0	26.85	0	26.85	31	13%
	RTG 10	4.82	4.82	0	26.18	0	26.18	31	16%
	RTG 11	4.47	4.47	0	26.54	0	26.54	31	14%
	RTG 12	9.54	9.54	0	21.46	0	21.46	31	31%

Note: Statistical time for each item is in days, small occurrences will be rounded to 15 min and converted to 0.01042 days (15/1440).

The actual survey showed that the quality of container handling does not meet the general requirements of the equipment groups as: quay crane (QC) 3%; yard crane (RTG) 2%; lift-on/lift-off vehicle (reach-stacker) 1%; and yard tractor 0%.

At Nam Dinh Vu terminal, quay cranes (QC) and yard cranes (RTG) only lift one 20′ container or one 40′ container for one time lifting the spreader, so the total MOVE is equal to the total throughput of 20′ and 40′ containers in the year. In 2021, the total throughput of the quay cranes (QC) group is 369,189 TEUs (in which the number of 20′ containers is 107,213 and the number of 40′ containers is 130,988), and the total number of MOVE Quay cranes (QC) group is 238,201. Therefore, the value of K_C of the quay cranes (QC) group is 1.55 (total output/total MOVE of QC crane block). Because the Nam Dinh Vu terminal does not separate the number of 20′ containers and containers for each handling of the yard crane (RTG) group, there is no basis for determining the Kc of the terminal's yard crane (RTG) group, and the quay cranes (QC) group and yard crane (RTG) group must ensure they meet the throughput of the terminal, so the K_C is assumed to be 1.55 as well.

Combined average handling-cycle time data in Table 2, container throughput of handling CHEs in Table 4, and the total operating time and availability (Ai) of each CHE in Table 6 in December 2021 at Nam Dinh Vu terminal, determined the value of performance (Pi), quality (Qi), OEEi of each CHE, and the OEE_G of the CHE group as shown in Table 7 below:

Table 7. Calculation of values of A, P, Q, OEEi, and OEE_G of Nam Dinh Vu terminal in December 2021.

Group of CHE	Codes	Average Handling Cycle Time of CHEs (Minute)	Total Throughput (TEU)	Percentage of Unqualified Throughput (%)	K_C (TEU/Move)	Total Operating Time		Availability of CHE-A (%)	Quality of CHE-Q (%)	Performance of CHE-P (%)	OEE_i (%)	OEE_G (%)
						Day	Minute					
Quay crane	QC 01	2.4	7083	3	1.55	9.46	13,622	31	97	80.51	24.21	31.65
	QC 02	2.4	10,684	3	1.55	14.25	20,520	46	97	80.62	35.97	
	QC 03	2.4	10,825	3	1.55	14.67	21,125	47	97	79.34	36.17	
	QC 04	2.4	8917	3	1.55	12	17,280	39	97	79.90	30.23	
Yard crane	RTG 01	2.4	5350	2	1.55	8.42	12,125	27	98	68.32	18.08	14.05
	RTG 02	2.4	5750	2	1.55	9.59	13,810	31	98	64.47	19.59	
	RTG 03	2.4	5500	2	1.55	9.09	13,090	29	98	65.06	18.49	
	RTG 04	2.4	5550	2	1.55	8.8	12,672	28	98	67.82	18.61	
	RTG 05	2.4	1150	2	1.55	1.96	2822	6	98	63.09	3.71	
	RTG 06	2.4	5200	2	1.55	7.51	10,814	24	98	74.45	17.51	
	RTG 07	2.4	2000	2	1.55	3.12	4493	10	98	68.93	6.75	
	RTG 08	2.4	5700	2	1.55	9.13	13,147	29	98	67.13	19.08	
	RTG 09	2.4	2450	2	1.55	4.16	5990	13	98	63.33	8.07	
	RTG 10	2.4	2900	2	1.55	4.82	6941	16	98	64.69	10.14	
	RTG 11	2.4	2650	2	1.55	4.47	6437	14	98	63.75	8.75	
	RTG 12	2.4	5800	2	1.55	9.54	13,738	31	98	65.37	19.86	

As shown in Table 7, the availability of CHEs (Ai) has the lowest value compared to performance (Pi) and quality (Qi). The Pi performance value of CHEs in the quay crane (QC) group is higher than that of the yard crane RTG group and the Pi performance value of CHEs in the same quay cranes (QC) or yard cranes (RTG) group is quite uniform. It can be seen that the availability factor (Ai) is an essential element to increase the value of the overall equipment effectiveness (OEEi). Therefore, it is necessary to periodically review the overall equipment effectiveness (OEE) (monthly or quarterly, or annually) to identify the causes and adjust the factors that help overcome problems to improve the productivity of each piece of equipment as well as the CHEs group.

4.2. Performance of Container Terminals in Vietnam

According to survey on terminal container throughput in the Hai Phong area and the Vietnam Seaport Association (VPA), Table 8 shows the performance of container terminals in the Hai Phong area over five years from 2017–2021.

It is obvious from Figure 4 that in the period 2017–2019, some ports' performance had low stability and the performance amplitude was considerably large, typically that of Tan Cang 128. As for Chua Ve Port, its performance for container cargo was lower than that of the other ports because this port exploits both bulk cargo and container cargo. The container terminal performance dropped in 2020 due to the COVID-19 pandemic but grew back in 2021. Although some terminals, such as Hai An, Tan Vu, and Vip Green Port, have performance exceeding 100% due to actual throughput exceeding the terminal design throughput, the operation of the remaining container terminals has not reached the design capacity. Therefore, it is necessary to measure and re-evaluate the performance of container terminals and then adjust the factors that help improve the terminals' performance. Based on the practices-analyzed performance and the field observation, there are relevant proposals related to the management of exploitation and maintenance of CHEs that would help improve the performance of CHEs and container terminals in Vietnam:

- Make a reasonable plan to allocate CHEs, especially equipment on the front lines of the port, to meet the cargo-handling needs of the ships and to ensure maximum utilization of the handling capacity of the CHEs, thereby improving the effectiveness of terminals;

- Monitor and regularly inspect the operating parameters of the CHEs to periodically evaluate the availability, performance, and quality of the CHEs, then make prompt adjustments contributing to the operational performance of the CHEs;
- Adjust and rearrange components of planned downtime (shift delivery time, shift meal time, and planned maintenance time) to minimize planned downtime of the CHEs;
- Develop a preventive maintenance plan [15] (periodic inspection, maintenance, and repair) by shift/week/month/year; organize the implementation of the maintenance plan based on the norms of time and materials; organizie prompt repair of abnormal damage of CHEs; and ensure maintenance activities are carried out as planned. These help: (1) improve the lifespan, durability, and availability of the CHEs; (2) minimize the possibility of unexpected damage, and unplanned downtime (time to stop the machine for emergency maintenance, repair abnormal damage, and downtime due to other subjective reasons that can be counted); and (3) minimize costs for CHEs' maintenance and other related losses caused by abnormal damage of the CHEs;
- Upgrade the handling technology and terminal-management technology [37,38] to meet the handling of demands of ships and to match general development trends around the world, thereby attracting more goods to the terminals; and
- Change the CHEs' management approach from manually-based management to fully computer software-aided management, optimizing maintenance of the CHEs. Information technology plays a vital role in improving the operational systems in cargo handling [39,40].

Table 8. Performance of container terminals in the Hai Phong area.

No.	Name of Terminal	Design Throughput of Terminal (TEU)	Năm									
			2017		2018		2019		2020		2021	
			Terminal Through-put (TEU)	Performance of Terminal	Terminal Through-put (TEU)	Performance of Terminal	Terminal Through-put (TEU)	Performance of Terminal	Terminal Through-put (TEU)	Performance of Terminal	Terminal Through-put (TEU)	Performance of Terminal
1	NAM HAI	200,000	163,800	82%	176,842	88%	141,633	71%	102,603	51%	130,441	65%
2	GREEN PORT	300,000	278,274	93%	324,379	108%	243,944	81%	227,190	76%	272,421	91%
3	CHUA VE	600,000	149,178	25%	261,000	44%	301,680	50%	325,163	54%	337,337	56%
4	TAN CANG 128	350,000	381,000	109%	323,591	92%	242,044	69%	141,863	41%	194,625	56%
5	HAI AN	350,000	381,987	109%	305,755	87%	312,504	89%	345,317	99%	414,547	118%
6	TAN CANG 189	150,000	140,479	94%	142,629	95%	109,132	73%	136,438	91%	141,949	95%
7	PTSC DINH VU	350,000	293,600	84%	320,312	92%	350,195	100%	341,515	98%	278,898	80%
8	DINH VU	650,000	688,170	106%	658,134	101%	544,282	84%	502,316	77%	583,172	90%
9	TAN VU	1,000,000	953,877	95%	890,000	89%	984,867	98%	948,947	95%	1,063,980	106%
10	NAM HAI DINH VU	550,000	629,498	114%	568,137	103%	455,906	83%	529,570	96%	549,044	100%
11	VIP GREEN PORT	500,000	453,924	91%	641,322	128%	638,897	128%	584,168	117%	635,647	127%
12	NAM DINH VU	500,000	-	-	184,531	37%	333,872	67%	258,255	52%	369,189	74%
13	HICT (LACH HUYEN)	1,000,000	-	-	64,920	6%	429,552	43%	661,065	66%	696,076	70%
14	MIPEC	250,000	-	-	-	-	-	-	8.950	4%	30,293	12%

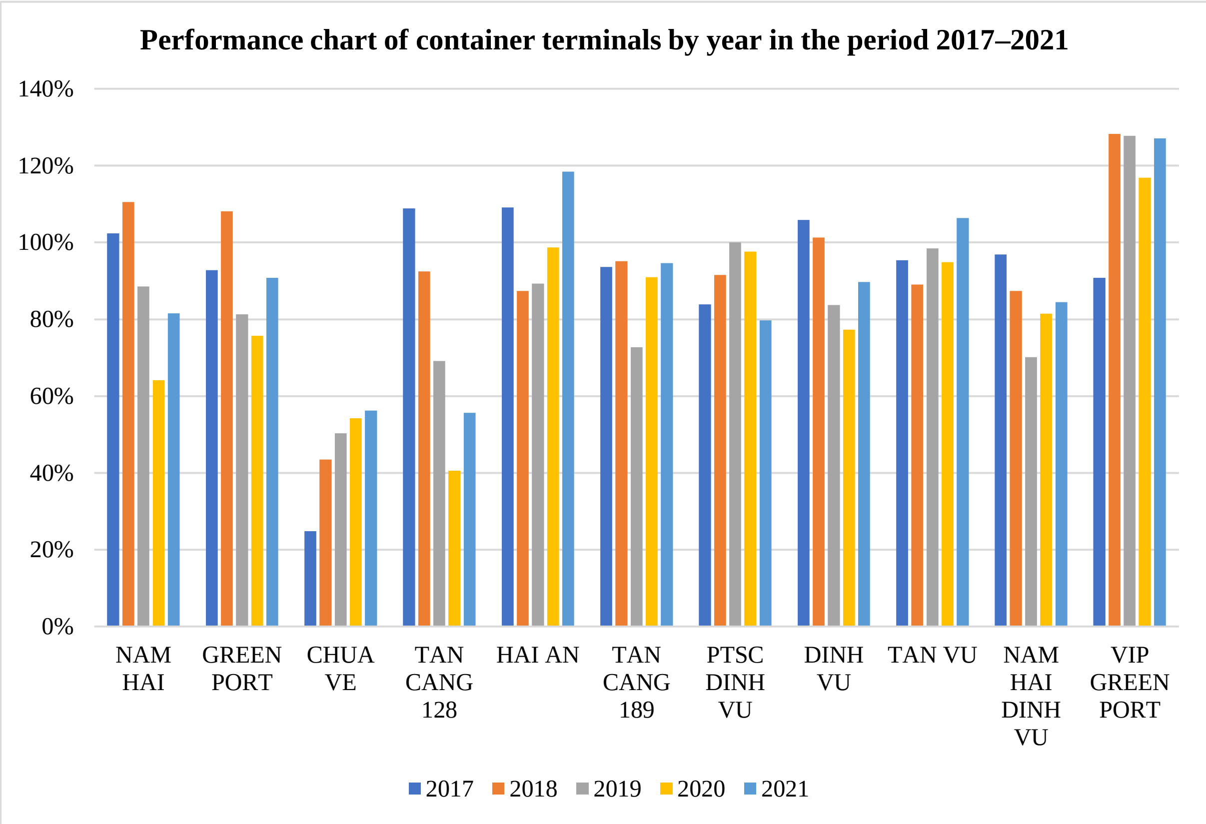

Figure 4. Container terminals' performance.

5. Conclusions

Through an empirical survey of 14 container terminals in Vietnam, the research proposed an application of the OEE technique for measuring the performance of CHEs in a container terminal. The findings reveal that the actual performance of CHE is still low, and the container terminals are operating at insufficient capacity, which means that their handling capacity has not been utilized thoroughly yet. Also, the low availability of CHEs indicates an essential reason for the decrease in the OEE of CHEs and container terminals' performance due to potential causes, such as out-of-date CHEs, inefficiency in use and maintenance of CHEs, and poor management as a whole. Therefore, to improve the capacity and performance of the CHEs, as well as the container terminals' performance, some necessary strategies are proposed that emphasize investing in the advanced CHE system and applying rational and synchronous solution management for CHEs.

Groups of CHEs' equipment in the container terminals have a close relationship with each other in the release of ships and goods through the port. The application of the OEE index for all groups of CHE equipment is an origin for assessing the influence of the overall performance between the groups of CHEs' equipment, thereby clarifying the relationship and influence of different parts to groups as well as to each group of CHEs' equipment. As a result, operating regulations can be developed for each group of CHEs' equipment and each division participate in the exploitation of the CHEs, thereby regulating the coordination of activities between groups of CHEs' equipment and management units of the terminal, maximizing the efficiency of the CHEs and the container terminals.

One of the limitations of this study is that the data were observed from practices in Vietnam and, therefore, are certainly valid for specific cases there, but their observation and applicability outside Vietnam are unclear. In addition, this study suffered from a relatively small sample size; increasing the volume of data could offer a comparative assessment using data from many case studies, which will provide a clearer understanding of how factors affected the CHEs' performance. Also, more data can offer regression analyses, thereby clarifying the causal relationship between potential predictors and the CHEs' performance.

Author Contributions: Conceptualization, H.T.P. and L.H.N.; methodology, L.H.N.; formal analysis, L.H.N.; investigation, H.T.P.; resources, H.T.P.; data curation, H.T.P.; writing—original draft preparation, H.T.P.; writing—review and editing, L.H.N.; visualization, H.T.P.; supervision, L.H.N.; project administration, L.H.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: There is no conflict of interest in this article and all our future articles.

References

1. Jeh, J.; Nam, J.; Sim, M.; Kim, Y.; Shin, Y. A Study on the Efficiency Analysis of Global Terminal Operators Based on the Operation Characteristics. *Sustainability* **2022**, *14*, 536. [CrossRef]
2. VILAS. Efficiency of Transporting Goods by Container. Available online: https://vilas.edu.vn/hieu-qua-cua-viec-van-chuyen-hang-hoa-bang-container.html (accessed on 2 May 2022).
3. Transport, M.O. The International Container Fleet Is Increasingly "Huge" in Size. Available online: https://www.mt.gov.vn/vn/tin-tuc/77462/doi-tau-container-quoc-te-ngay-cang--khung--ve-kich-co.aspx (accessed on 2 May 2022).
4. Saxon, S.; Stone, M. *Container Shipping: The Next 50 Years*; McKinsey & Company: Travel, Transport & Logistics: Hong Kong, China, 2017.
5. Securities, K. *Port Industry Report—Difficult Outlook for 2020 Due to the Impact of Corona Virus—Positive Long-Term Outlook Due to Favorable Macro Developments*; KB Securities: Hanoi, Vietnam, 2020; Available online: https://www.kbsec.com.vn/pic/Service/SECTOR_SEAPORT_VN.pdf (accessed on 2 May 2022).
6. Mihajlović, J.; Rajković, P.; Petrović, G.; Ćirić, D. The selection of the logistics distribution center location based on MCDM methodology in southern and eastern region in Serbia. *Oper. Res. Eng. Sci. Theory Appl.* **2019**, *2*, 72–85. [CrossRef]
7. Vesković, S.; Stević, Ž.; Nunić, Z.; Milinković, S.; Mladenović, D. A novel integrated large-scale group MCDM model under fuzzy environment for selection of reach stacker in a container terminal. *Appl. Intell.* **2022**, 1–25. [CrossRef]
8. Vietnam Maritime Administration. *Project to Improve the Efficiency of Management and Operation of the Existing Hai Phong Seaport and Lach Huyen Port Area*; Vietnam Maritime Administration: Hanoi, Vietnam, 2019.
9. Ju, S.-M.; Liu, N. Efficiency and its influencing factors in port enterprises: Empirical evidence from Chinese port-listed companies. *Marit. Policy Manag.* **2015**, *42*, 571–590.
10. Suárez-Alemán, A.; Sarriera, J.M.; Serebrisky, T.; Trujillo, L. When it comes to container port efficiency, are all developing regions equal? *Transp. Res. Part A Policy Pract.* **2016**, *86*, 56–77.
11. De Oliveira, G.F.; Cariou, P. The impact of competition on container port (in) efficiency. *Transp. Res. Part A Policy Pract.* **2015**, *78*, 124–133. [CrossRef]
12. Luna, J.H.; Mar-Ortiz, J.; Gracia, M.D.; Morales-Ramírez, D. An efficiency analysis of cargo-handling operations at container terminals. *Marit. Econ. Logist.* **2018**, *20*, 190–210.
13. Wojcik, V.; Dyckhoff, H.; Clermont, M. Is data envelopment analysis a suitable tool for performance measurement and benchmarking in non-production contexts? *Bus. Res.* **2019**, *12*, 559–595. [CrossRef]
14. Cook, W.D.; Tone, K.; Zhu, J. Data envelopment analysis: Prior to choosing a model. *Omega* **2014**, *44*, 1–4. [CrossRef]
15. Phạm, H.T.; Nguyễn, L.H. Research on the current situation of management and exploitation of loading and unloading equipment at container ports with state-owned shares. *J. Transp.* **2021**, *4*, 142–147.
16. Lanza, G.; Stoll, J.; Stricker, N.; Peters, S.; Lorenz, C. Measuring global production effectiveness. *Procedia CIRP* **2013**, *7*, 31–36.
17. Paris, A.D. Overall Equipment Effectiveness-OEE: Necessário, Mas não Suficiente: Uma Análise Integrando o OEE e a Data Envelopment Analysis-DEA. 2016. Available online: http://www.repositorio.jesuita.org.br/handle/UNISINOS/6036 (accessed on 2 May 2022).
18. Jeong, K.Y.; Phillips, D.T. Operational efficiency and effectiveness measurement. *Int. J. Oper. Prod. Manag.* **2001**, *21*, 1404–1416. [CrossRef]
19. Muchiri, P.; Pintelon, L. Performance measurement using overall equipment effectiveness (OEE): Literature review and practical application discussion. *Int. J. Prod. Res.* **2008**, *46*, 3517–3535. [CrossRef]
20. Jo, J.-H.; Kim, S. Key performance indicator development for ship-to-shore crane performance assessment in container terminal operations. *J. Mar. Sci. Eng.* **2019**, *8*, 6. [CrossRef]
21. Mouafo Nebot, G.V.; Wang, H. Port Terminal Performance Evaluation and Modeling. *Logistics* **2022**, *6*, 10.

22. Pinto, M.M.; Goldberg, D.J.; Cardoso, J.S. Benchmarking operational efficiency of port terminals using the OEE indicator. *Marit. Econ. Logist.* **2017**, *19*, 504–517.
23. Mazloumi, M.; van Hassel, E. Improvement of Container Terminal Productivity with Knowledge about Future Transport Modes: A Theoretical Agent-Based Modelling Approach. *Sustainability* **2021**, *13*, 9702. [CrossRef]
24. Jeon, J.; Kim, C.; Lee, H. Measuring efficiency of total productive maintenance (TPM): A three-stage data envelopment analysis (DEA) approach. *Total Qual. Manag. Bus. Excell.* **2011**, *22*, 911–924.
25. Andersson, C.; Bellgran, M. On the complexity of using performance measures: Enhancing sustained production improvement capability by combining OEE and productivity. *J. Manuf. Syst.* **2015**, *35*, 144–154.
26. Jain, A.; Bhatti, R.; Singh, H. Total productive maintenance (TPM) implementation practice: A literature review and directions. *Int. J. Lean Six Sigma* **2014**, *5*, 293–323. [CrossRef]
27. Team, N.P.E. *Maintain Overall Device Performance—TPM: Basic Content and Application Guidelines*; Hồng Đức: Thanh Hoa, Vietnam, 2018.
28. Winmain CMMS. Overall Equipment Effectiveness. Available online: https://winmaincmms.com/phan-mem-quan-ly-bao-tri-hieu-suat-toan-dien/ (accessed on 2 May 2022).
29. Vu le Technology Co., L. Importance of OEE Equipment Overall Performance. Available online: https://vuletech.com/tam-quan-trong-cua-hieu-suat-tong-the-thiet-bi-oee/ (accessed on 2 May 2022).
30. Phan, T.M.H. Method of Estimating Cycle Time for Container Loading and Unloading to Forecast System Operating Capacity. Industry and Trade Magazine 2017. Available online: http://tapchicongthuong.vn/bai-viet/phuong-phap-uoc-tinh-thoi-gian-chu-ky-cho-viec-boc-do-container-nham-du-bao-cong-suat-hoat-dong-cua-he-thong-51222.htm (accessed on 2 May 2022).
31. Notteboom, T.; Pallis, A.; Rodrigue, J.-P. *Port Performance: The Efficiency Continuum*; Routledge: London, UK, 2022.
32. Ha, M.H. *The Influence of Port Characteristics on the Efficiency of Container Port Operations in Vietnam*; University of Economics Ho Chi Minh City: Ho Chi Minh, Vietnam, 2020.
33. Nguyen, T.T. *Port Economics*; Statistics Publisher: Geneva, Switzerland, 2012.
34. Jaffar, W.D.; Berry, G.A.; Ridley, I. Performance management in port authorities. *Marit. Herit. Mod. Ports* **2005**, *79*, 269–278.
35. Securities, V. *Port Industry Prospect Report—Logistics 2022—Recovery of Growth Momentum*; Vietcombak Securities: Hanoi, Vietnam, 2021; Available online: http://vcbs.com.vn/vn/Communication/GetReport?reportId=9257 (accessed on 2 May 2022).
36. Securities, F. *Port Industry Report—Upgrade Infrastructure to Drive Growth*; FPT Securities: Hanoi, Vietnam, 2017; Available online: http://static1.vietstock.vn/edocs/5802/Marine_Port_Report_072017_FPTS.pdf (accessed on 2 May 2022).
37. EPA U S. National Port Strategy Assessment: Reducing Air Pollution and Greenhouse Gases at US Ports. Environmental Protection Agency: Office of Transportation Air Quality. 2016; EPA-420-R-16-011. Available online: http://www.epa.gov/airmarkets/trading (accessed on 2 May 2022).
38. Nyema, S.M. Factors influencing container terminals efficiency: A case study of Mombasa entry port. *Eur. J. Logist. Purch. Supply Chain. Manag.* **2014**, *2*, 39–78.
39. Kia, M.; Shayan, E.; Ghotb, F. The importance of information technology in port terminal operations. *Int. J. Phys. Distrib. Logist. Manag.* **2000**, *30*, 331–344. [CrossRef]
40. Song, Z.; Lin, W.X.; Yue, W.F.; Dong, L.D.; Rong, Z.; Lin, K.W.; Dong, C.X.; Wang, C.D. Applying the parallel systems approach to automatic container terminal. *Acta Autom. Sin.* **2019**, *45*, 490–504.